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# Aerospace Energy Systems Laboratory: Requirements and Design Approach

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AEROSPACE ENERGY SYSTEMS LABORATORY:  
REQUIREMENTS AND DESIGN APPROACH

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ABSTRACT

The NASA Ames-Dryden Flight Research Facility at Edwards, California operates a mixed fleet of research aircraft employing nickel-cadmium (NiCd) batteries in a variety of flight-critical applications. Dryden's Battery Systems Laboratory (BSL), a computerized facility for battery maintenance servicing, has evolved over two decades into one of the most advanced facilities of its kind in the world. Recently a major BSL upgrade was initiated with the goal of modernization to provide flexibility in meeting the needs of future advanced projects. The new facility will be called the Aerospace Energy Systems Laboratory (AESL) and will employ distributed processing linked to a centralized data base. AESL will be both a multistation servicing facility and a research laboratory for the advancement of energy storage system maintenance techniques. This paper describes the baseline requirements for the AESL and the design approach being taken for its mechanization.

INTRODUCTION

For many years the NASA Ames Research Center's Dryden Flight Research Facility (Ames-Dryden) has been operating research aircraft in which rechargeable batteries serve as important power sources for various flight-critical systems. It is essential that such batteries undergo periodic servicing, which verifies integrity, capacity, and load-carrying ability, in order to renew their flight safety certification. Servicing cycles vary from a few weeks to several months, and any batteries that do not meet standards are refurbished or taken out of service. Due to the large number of aircraft, each of which has several sets of batteries assigned to it, the servicing workload is considerable. Ames-Dryden has been incorporating automation techniques to lower the cost of battery servicing, while at the same time improving quality and reducing turnaround times.

The present Ames-Dryden Battery Systems Laboratory (BSL) evolved over a time span of 20 years, based

on goals established in the 1960s. At that time Ames-Dryden was heavily involved in battery servicing in support of flight testing of various lifting body aircraft. Lifting bodies are wingless rocket-powered research aircraft that were flight-tested by releasing them at high altitude and maneuvering them to a prearranged landing point. Since lifting bodies had no rotating electrical generators, all power to operate avionics systems, hydraulic pumps, radios, and instrumentation was provided by silver-zinc (AgZn) batteries. These batteries were charged prior to each flight using constant potential charging equipment, but cell imbalance problems necessitated individual cell monitoring. Such manual procedures were very time-consuming and prone to error, and similar problems were later experienced as nickel-cadmium (NiCd) batteries came into wide use. Even today, proper battery servicing continues to be a perennial problem for the Department of Defense (DoD) and the commercial airlines.

In 1970 automation was first introduced into the BSL using a commercial minicomputer and a 200-channel scanner employing a multiplexed analog-to-digital converter (ADC). The scanner monitored battery current and individual cell voltages using a clamp-on monitor plate incorporating spring-loaded contacts. The chargers were modified to provide a computer interface so that automatic shutdown could be remotely commanded. This system was so successful that in 1973 the minicomputer was upgraded and the ADC expanded to 800 channels. A modernization effort beginning in 1979 brought the system up to 1024 ADC channels, and a new computer system allowed control over 40 battery-charging stations.<sup>(1)</sup>

In 1987 it was decided that the BSL required further modernization to bring it up to the current state of the art in computerization and data acquisition. The second-generation BSL will be called the Aerospace Energy Systems Laboratory (AESL), in keeping with its expanded charter to support anticipated flight testing of advanced aircraft, including the National Aerospace Plane (NASP) now under development. This report will discuss the

new facility requirements that have evolved from experience gained in the BSL. In addition, the report will present a design approach that capitalizes on systems engineering done at Ames-Dryden in support of aircraft testing.(2,3)

#### BACKGROUND

The servicing of NiCd batteries presents several problems that stem from the unusual chemistry of the sintered plates and their interaction with the electrolyte.(4) For aircraft-type NiCd batteries, the plates consist of a sintered matrix of inert metallic nickel impregnated with reactants immersed in a solution of 30 percent potassium hydroxide (KOH) in distilled water. In a fully charged NiCd battery, the positive plates are impregnated with nickel oxy hydroxide (NiOOH), and the negative plates are impregnated with metallic cadmium (Cd). During discharge, water is removed from the electrolyte as both of these reactants are converted to metallic hydroxides; the KOH itself does not take part in the reaction.

One problem in dealing with NiCd batteries is that it is difficult to determine the state of charge of the battery. The electrolyte does undergo a slight specific gravity change during discharge, but the state of charge of a NiCd battery cannot be accurately determined by measuring electrolyte specific gravity, as is the case in ordinary lead-acid batteries. Likewise, battery voltage is not a good indicator of state of charge because the open circuit voltage remains remarkably constant, independent of state of charge.

A second problem frequently observed in NiCd batteries is the phenomenon of "memory," which causes the capacity of a battery to gradually decrease with each successive discharge-charge cycle. This is due to cell imbalances and can usually be corrected by deep discharging each cell to zero volts and then recharging.

A third problem is the potential for electrolyte contamination. Atmospheric carbon dioxide will combine with the KOH to form carbonates if the cell caps are left off for extended periods of time during servicing. A second source of contamination is fumes from lead-acid batteries if they are serviced in close proximity to the NiCd servicing area. It is mandatory that only distilled or deionized water be added to a NiCd cell to make up for loss due to evaporation and electrolysis.

Two problems can occur during NiCd battery charging that have the potential for cell damage and operator hazard. The first is explosive hydrogen liberated during normal charging by electrolysis; this problem is made worse by overcharging. Figure 1 shows the consequences of ignition of hydrogen trapped in a NiCd cell. Another problem is the damaging effects of overtemperature during charging. A phenomenon called thermal runaway can occur at high charging rates leading to plate

separator breakdown. This eventually results in short circuit self-discharge of the cell; Figure 2 shows one possible result where the plastic cell case was melted through.

#### BATTERY SYSTEM LABORATORY (BSL) OVERVIEW

Figure 3 shows the methodology that evolved in the BSL to service a NiCd battery (the main type presently used in Ames-Dryden aircraft). The procedure goes well beyond the battery manufacturer's recommended servicing and is believed to be the most exhaustive servicing done anywhere. It covers three different aspects: (1) assessing condition upon removal from the aircraft, (2) assessing capacity, and (3) assessing load-carrying ability. During the course of this procedure, the battery is recharged several times and receives numerous inspections.

The purpose of assessing battery condition upon removal from the aircraft is two-fold. First, it is an indicator of the health of the aircraft electrical system since damage can result from either under-charging or over-loading (such as short circuits). Second, it detects battery damage due to operational abuses, such as handling mishaps and temperature extremes. The case leakage test is designed to detect electrolyte spillage due to cell rupture or venting from the filler cap. The return capacity test measures residual ampere-hours (A-H) and indicates whether safety margins remain adequate in the particular application. Following this, each cell in the battery is fully discharged using individual load resistors, thus minimizing the memory phenomenon.

The main capacity test is performed after a full charge (No.1) has been placed into the battery and the battery has been allowed to cool. During charging, the battery must be monitored for proper current, cell voltages, and temperature. During discharge these same parameters must remain within normal limits, and in addition, the integrated A-H must meet or exceed rated capacity. Since subsequent charging has the same cutoff conditions as charge No. 1, the main capacity test is believed to accurately predict the state of charge when the battery is ultimately returned to service.

The load test is performed after a second full charge (No.2) has been placed into the battery and the battery is allowed to cool again. During charging, not only must current, voltage, and temperature remain within limits, but intercell voltage differences are closely watched to detect any imbalances. During load test, a high current drain is briefly placed on the battery using either a constant load or a programmed variable current profile. This determines the battery's ability to deliver expected demands in the aircraft while maintaining proper voltage level. A final charge (No.3) is placed in the battery immediately before delivery, and a final leakage test is performed to verify cell integrity. A quality assurance buy-off completes the servicing cycle.

Figure 4 shows an overview of the present BSL configuration. After many years of useful service, this equipment is nearing obsolescence and will be totally replaced during the transition to the AESL configuration. In addition, certain architectural changes are planned, owing to what is now believed to be a shortcoming of the present architecture: Both the data acquisition system and the controller system are centralized and as such constitute single-point failures.

Figure 5 shows a typical battery being serviced at station 35 with the monitor plate clamped to the top of the battery case. The wiring harness visible in the background is routed along an overhead cable ladder and connects the station bench to the central ADC. This type of wiring represents a further disadvantage of centralized ADC: It prevents the benches from being easily relocated to accommodate floor plan changes.

Figure 6 shows the current and voltage waveforms for the most commonly used charger in the BSL: the Christie Reflex Charger/Analyzer. The pulse waveshape creates problems of electromagnetic interference and inaccurate measurement of current and voltage due to insufficient sample rate of the present ADC. This causes improper A-H integration and makes the values displayed to the operator very noisy.

#### AEROSPACE ENERGY SYSTEMS LABORATORY (AESL)

##### Requirements

The final overall requirements for the AESL may be broken into the following five categories:

##### Improve Reliability —

- o New state-of-the-art hardware
- o Decentralized architecture to reduce wiring
- o Industrial grade real-time operating system
- o Fault-tolerant partitioned system philosophy
- o Stand-alone operations of system components

##### Upgrade Central System —

- o Incorporate battery-specific servicing history archive
- o Incorporate project-specific applications data base
- o Incorporate battery-type characteristics data base
- o Incorporate independently powered clock and calendar

##### Improve Safety —

- o Incorporate cell emissions detector
- o Incorporate case temperature sensing
- o Incorporate runaway cell detection algorithm
- o Incorporate deadman timers in control loops
- o Provide independent primary power shut-down relays

##### Improve Accuracy —

- o Increase data acquisition sample rate
- o Perform amp-hour integration at 100 Hz or more
- o Incorporate algorithms for pulsed waveform analysis
- o Incorporate provisions for ADC calibration

##### Improve Productivity —

- o Provide operator I/O at each battery station
- o Minimize operator keyboard operations
- o Provide rapid battery identification by bar-code tags
- o Automate case leakage current measurement
- o Permit unattended overnight and weekend operations

##### Overview

Figure 7 shows the proposed architecture of the AESL. The central system is a commercially available 80286-based microcomputer system with an added 80287 numeric data processor. The basic system will be augmented with a multiple-user input/output (I/O) interface, a serial bus controller, and a battery-powered clock/calendar. The serial data bus employs the RS-485 physical link standard with a communications protocol that is a subset of ordinary synchronous data link control (SDLC). The central system is the bus supervisor and continuously polls the slave bus interface hardware in each of the addressable battery stations. The presently planned initial configuration is for a complement of 10 battery stations, 7 of which will host reflex chargers, and 3 of which will host constant current chargers.

Figure 8 shows the hardware suite for a typical battery station. The controller has been engineered at Ames-Dryden and is built of board components compatible with the Institute of Electrical and Electronic Engineers IEEE-796 standard. The power to the charger/analyzer is controlled by means of a pair of heavy duty mercury displacement relays. A high-precision 100 mV/100 ampere shunt will be used to monitor battery current. The monitor plate provides voltage pickoffs on each cell of the battery and also contains a single temperature sensor to detect hot emissions (if any) from the pressure relief valves in the cell filler caps. Four additional temperature probes will be placed under the battery case to detect overtemperature conditions internal to the battery. The interface to the external programmable load bank allows current control and monitoring.

Figure 9 shows the build-up of a typical battery station controller. Its central processor unit (CPU) is a commercial 8086-based single-board computer that has a 8087 numeric data processor (NDP) installed. Also mounted piggy-back on this board is the serial bus interface module. The ADC subsystem consists of two boards: an intelligent

main board with 16 input channels and an expander board permitting an additional 32 channels to be scanned. The main board employs a Z80 microprocessor programmed (by NASA) to scan the 48 channels, based on information contained in a control matrix loaded by the CPU. Discrete I/O is accomplished using a single-board unit configured as transistor-transistor logic (TTL) level interfaces for the operator status and control panel (SCP). The digital-to-analog-converter (DAC) board provides a single channel of 0 to 10V to control the external programmable load bank. The bubble memory consists of two 128-Kbyte cartridges, one of which contains the program software, the other is used for data storage.

Figure 10 shows the proposed layout of the SCP for each battery station. This unit gives the operator sufficient control and monitoring for normal operations (when central system services are available) such that a terminal is not required. In addition, it will serve as a caution and warning device giving messages in plain English for abort conditions. All software interfaces will be structured so that an operator need not be trained in computer operations to perform routine battery servicing.

Figure 11 shows how the proposed AESL will function. The operator interfaces at the battery station consist of a hand-held barcode reader gun, the SCP, and a beeper alarm. The identifying barcode tag on the side of the battery is read, and the appropriate data base files are transferred from the central system. The operator attaches the monitor plate and temperature probes, selects the mode of operation using the SCP, sets up the proper settings on the charger/analyzer, and initiates the operation. At the completion of the operation, the station controller shuts down the charger, alerts the operator, and transfers the data generated during the operation to the central system to be archived. At all times, the complete servicing history for each battery is accessible for review using a terminal. In addition, the central system has the real-time status of each battery station available for review using a terminal.

The software for the AESL will be configured such that a battery station can be operated in stand-alone fashion if for any reason the services of the central system are not available. Such might be the case if, for example, the battery station is transported to a remote location, or if the central system is down for maintenance. In this mode of operation, the operator must plug a terminal into the station and configure its software manually. Any servicing records generated are temporarily stored in bubble memory for later transfer to the central system. A line printer port is also available, should the operator wish to make immediate hard copies of any of the data.

This proposed AESL design provides increased safety margins in the two principal areas of concern: overtemperature and electrolysis. The main guardian in the prevention of overtempera-

ture is the runaway cell detection algorithm in the battery station controller software. This algorithm will immediately detect any cell voltage drop during charging and will shut down the charger. The battery case temperature probes will provide additional safety margin, but the response is sufficiently slow that negative cell  $dv/dt$  is expected to be the main sensing means. While electrolysis and accompanying hydrogen gas liberation are not directly detectable (without a hydrogen gas detector), the hot emissions temperature probe at the top of the battery is expected to quickly show a temperature rise should major releases occur. If the controller software senses that this temperature readout violates a preset threshold, charging operations are shut down. The responsible cell(s) can then be identified by visual inspection.

An additional safety feature is the fail-safe design of the charger/analyzer shutdown circuitry. The primary power relays that are external to the charger are controlled by a hardware deadman timer in the controller CPU. This timer is in the form of a retriggerable one-shot multivibrator that has a 100 msec period. The controller software must retrigger the one-shot at greater than a 10 Hz rate; should either hardware failure or software error prevent it from doing so, the deadman opens the relays. Once the relays open, the charger can only be brought back on line by the operator.

#### Development Plan

The initial phase of AESL development will be devoted to the construction of a prototype battery station module. This prototype will be tested initially in stand-alone mode; following initial verification and validation in the engineering laboratory, it will be turned over to BSL personnel for a 30-day shakedown. Special emphasis will be given to testing the operator interface routines and to the charger waveform analysis algorithms.

The second phase of the effort will concentrate on the construction and programming of the central system. A large amount of effort is anticipated to develop the data base file structures and support software. The system will finally be tested on the data bus with the prototype battery station to evaluate bus traffic message structures and transport time delay effects. The user terminal interfaces will be checked out both in data terminal interface (DTI) mode and in modem channel mode.

The final phase of the effort will be the construction of the first 10 production battery station modules. The prototype will become an engineering brassboard used to develop and evaluate new software.

#### CONCLUDING REMARKS

The existing NASA Ames-Dryden BSL has provided a wealth of operations experience in the servicing of aircraft batteries and has accumulated a large

data base of historical records. Its computerized system has been commended by battery manufacturers and other government agencies involved in similar servicing operations. The requirements for the new AESL build on this experience by specifying numerous enhancements while retaining proven features. Similarly, the proposed mechanization for the AESL builds on proven systems design experience gained from other programs at Ames-Dryden. The resulting AESL design is believed to offer a highly cost-effective approach to meeting the design requirements.

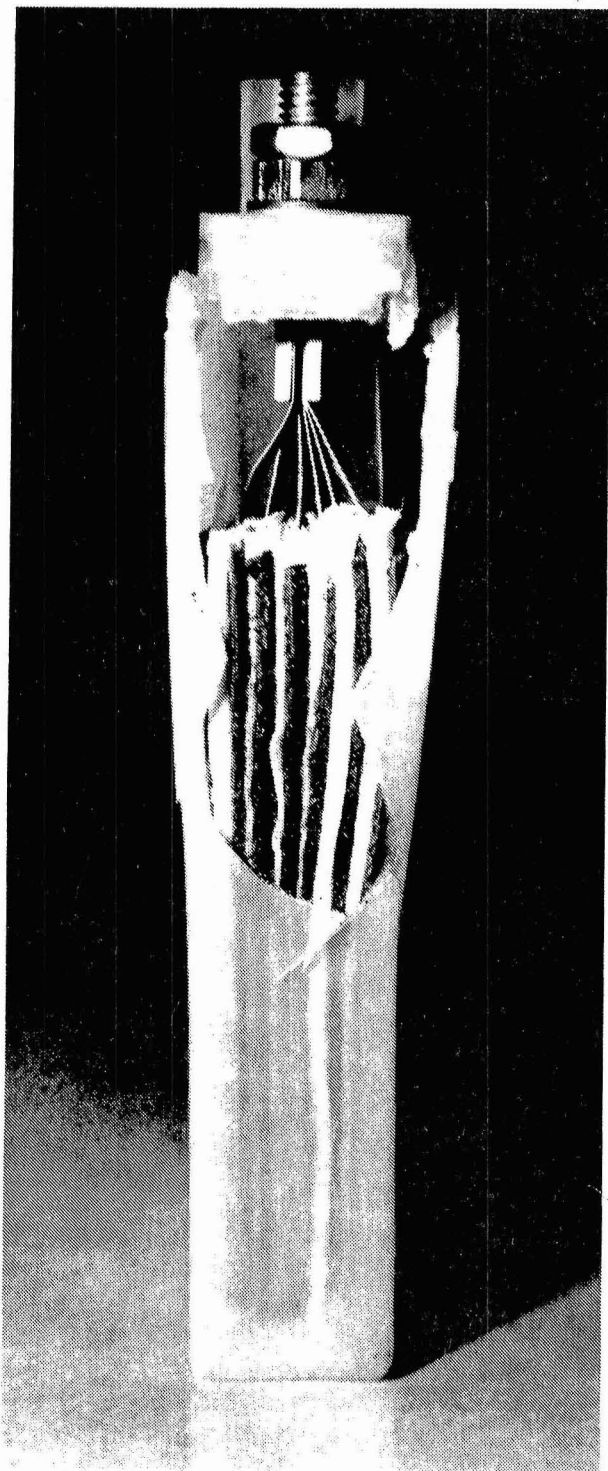
#### NOMENCLATURE

ADC	analog-to-digital converter
AESL	Aerospace Energy Systems Laboratory
AgZn	silver-zinc
A-H	ampere-hours
Ames-Dryden	NASA Ames Research Center, Dryden Flight Research Facility
BSL	Battery Systems Laboratory
Cd	cadmium
CPU	central processing unit
DAC	digital-to-analog converter
DoD	Department of Defense
DTI	data terminal interface
IEEE	Institute of Electrical and Electronic Engineers

I/O	input/output
KOH	potassium hydroxide
NASP	national aerospace plane
NDP	numeric data processor
NiCd	nickel-cadmium
NiOOH	nickel oxy hydroxide
SCP	status & control panel
SDLC	synchronous data link control
TTL	transistor-transistor logic

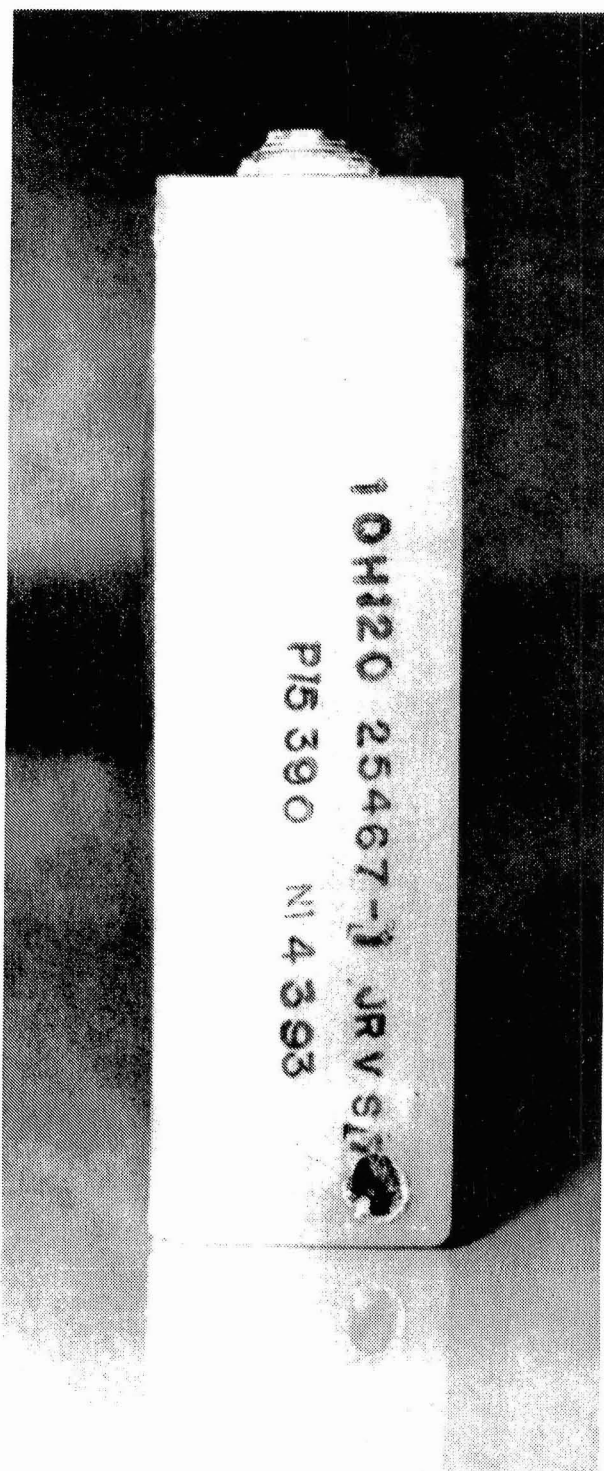
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- <sup>1</sup>Stewart, Alphonzo J., "NASA Ames-Dryden Flight Research Facility Battery Systems Laboratory," NASA TM-84905, Aug. 1982.
- <sup>2</sup>Glover, Richard D., "Application Experience With the NASA Aircraft Interrogation and Display System: A Ground-Support Equipment for Digital Flight Systems," proceedings of IEEE/AIAA 5th Digital Avionics Systems Conf., Seattle, Wash., Oct. 31 - Nov. 3, 1983, pp. 17.3.1-17.3.10.
- <sup>3</sup>Glover, Richard D., "Design and Initial Application of the Extended Aircraft Interrogation and Display System: Multiprocessing Ground Support Equipment for Digital Flight Systems," NASA TM-86740, Jan. 1987.
- <sup>4</sup>Care and Maintenance of Nickel-Cadmium Batteries, Instruction Manual BA-89 Rev. 886, Marathon Battery Company, Waco, Texas.



EC87 0178-004

*Figure 1. Explosive failure of NiCd cell.*



EC87 0178-003

*Figure 2. Overtemperature failure of NiCd cell.*



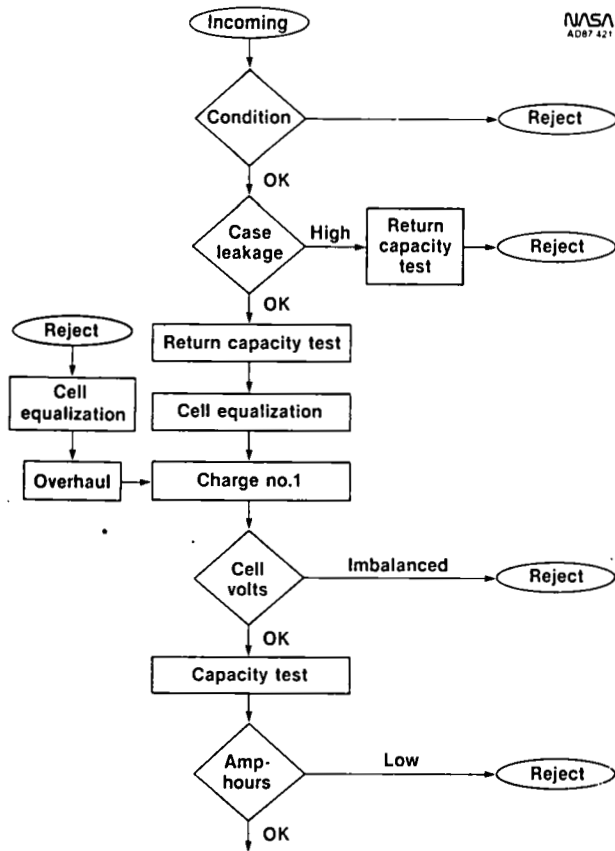


Figure 3. BSL servicing flow.

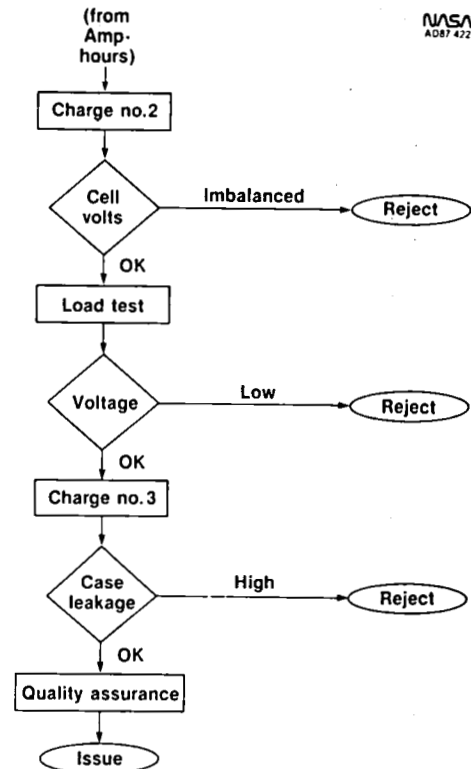


Figure 3. Concluded.

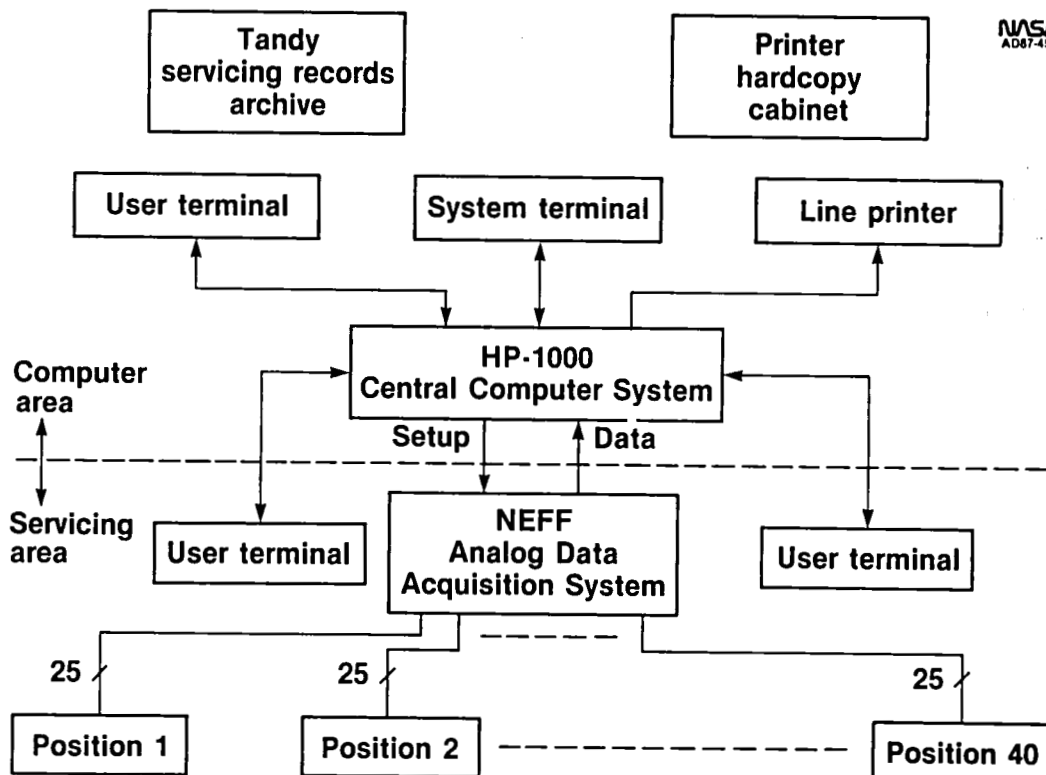
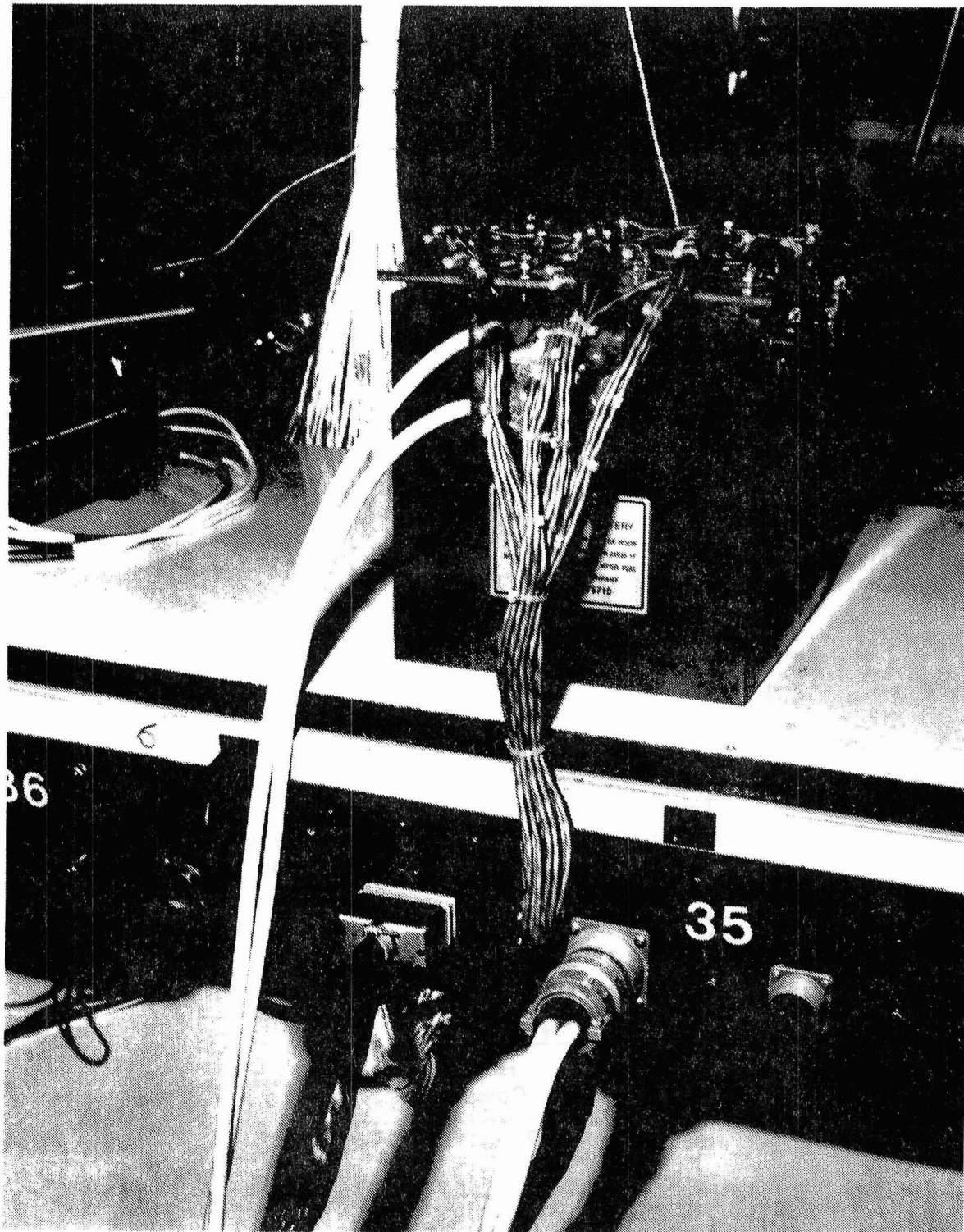


Figure 4. BSL architectural overview.



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*Figure 5. Typical BSL battery station.*

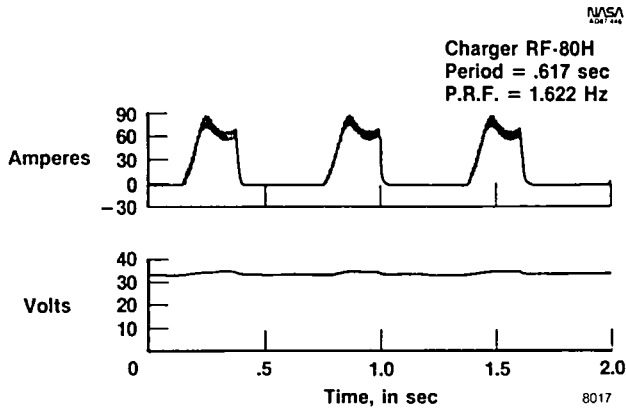


Figure 6. BSL reflex charger waveforms.

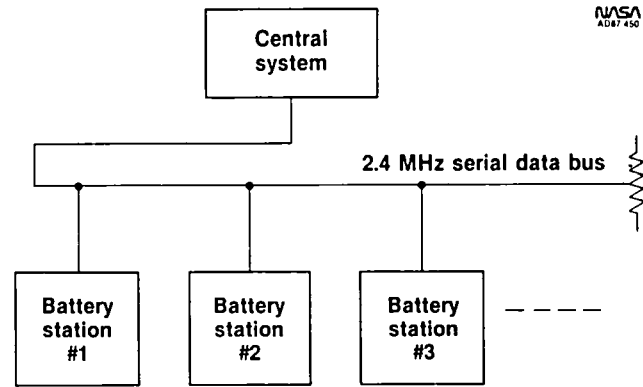


Figure 7. AESL architectural overview.

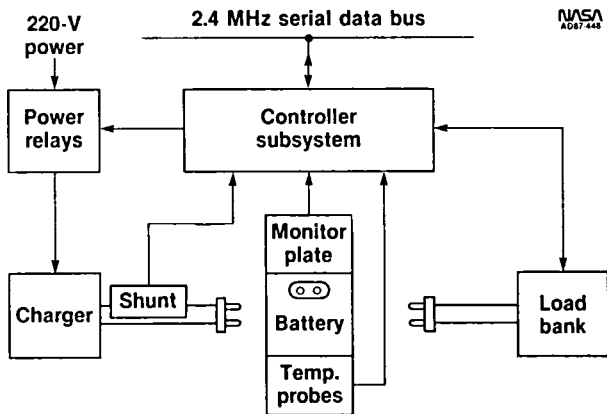


Figure 8. AESL battery station.

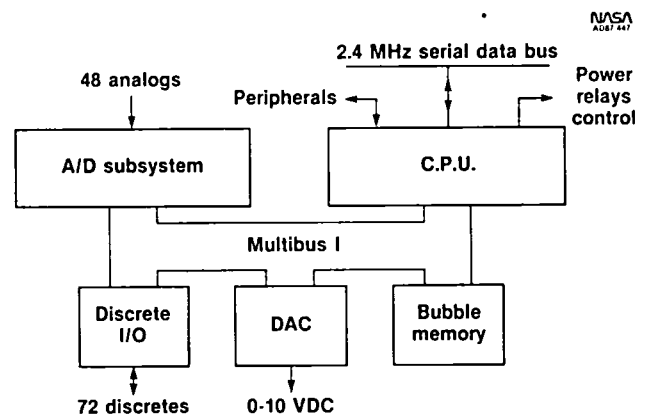


Figure 9. AESL battery station controller.

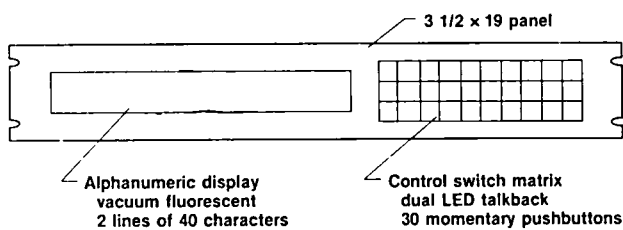


Figure 10. AESL battery station status and control panel.

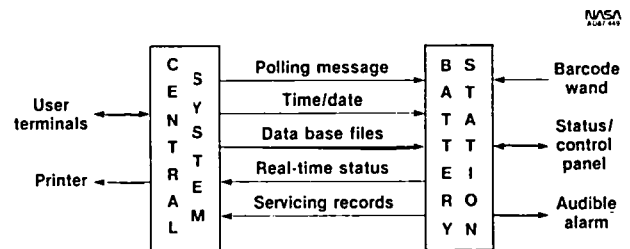


Figure 11. AESL functional overview.

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